

Electroweak and QCD corrections to Higgs production in vector-boson fusion at the LHC

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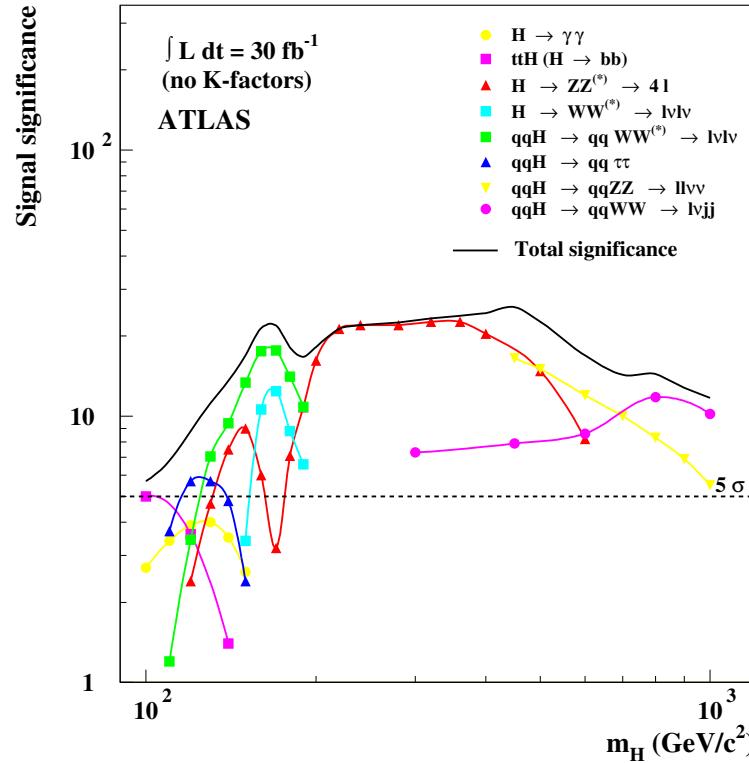
Physics at TeV colliders, Les Houches, June 11–29, 2007

in collaboration with M. Ciccolini and S. Dittmaier

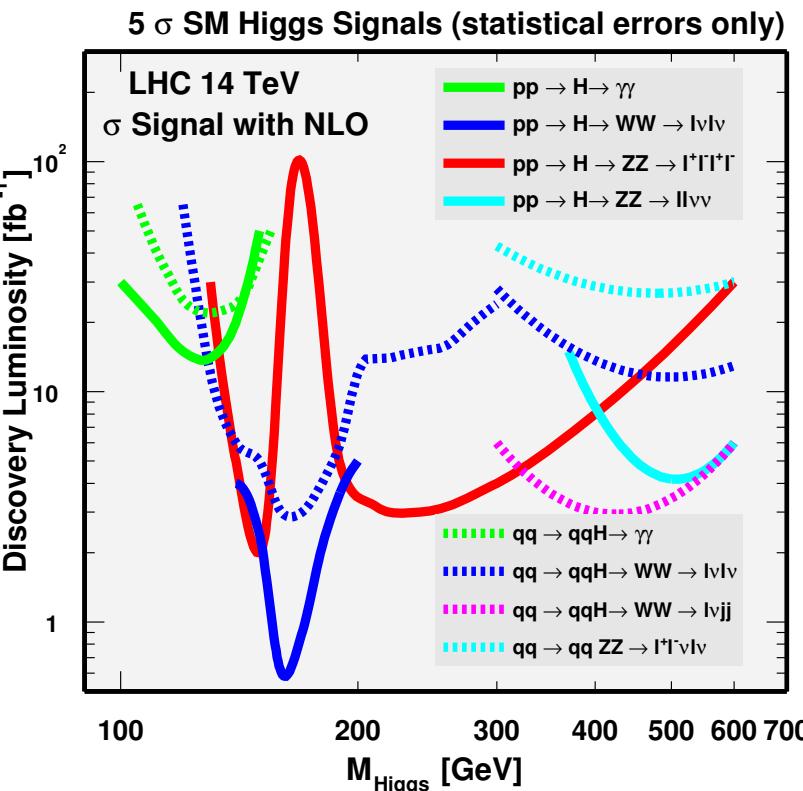
- Motivation
- Some details of the calculation
- Numerical results

Introduction — Significance of Higgs signal at LHC

ATLAS '04



CMS



Importance of vector-boson fusion (VBF) $pp \rightarrow H + 2\text{jets} + X$:

- important Higgs-production process for $100 \text{ GeV} \lesssim M_H \lesssim 200 \text{ GeV}$ and large Higgs boson masses
- measurement of HVV couplings

Experimental versus theoretical uncertainties for vector boson fusion

expected experimental uncertainty for $\sigma \times B$: 5–10% Zeppenfeld et al '00

NLO corrections to $pp \rightarrow H + 2\text{jets} + X$

neglecting all interferences \Rightarrow only vertex corrections (structure functions)

- total cross section:

Han, Valencia, Willenbrock '92; Spira '98; Djouadi, Spira '00

corrections increase LO by $\sim 5\text{--}10\%$

residual scale dependence: few per cent

leading corrections absorbed in PDFs

- cross section with realistic vector-boson fusion (VBF) cuts, jet distributions:

Figy, Oleari, Zeppenfeld '03, Berger, Campbell '04

corrections of the order of 10–20%, strongly phase-space dependent

- theoretical uncertainty from QCD: $\pm 4\%$ Figy, Oleari, Zeppenfeld '03

Size of electroweak (EW) corrections?

First results for electroweak corrections

Ciccolini, Denner, Dittmaier '07

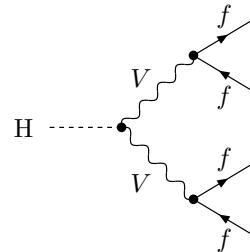
- complete NLO electroweak corrections to $pp \rightarrow H + 2\text{jets} + X$ including photon-induced processes
- recalculation and extension of NLO QCD correction
(complete set of diagrams and interference contributions)

calculation follows closely the one for $H \rightarrow 4f$

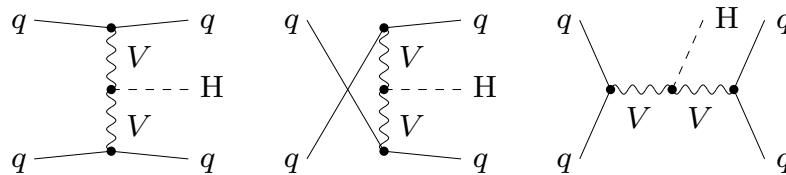
Bredenstein, Denner, Dittmaier, Weber '06/'07

diagrams can be obtained via crossing symmetry

LO topology for $H \rightarrow 4f$

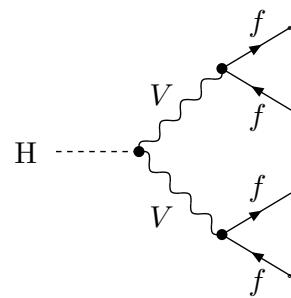


topologies for t -, u -, and s -channel contributions to $qq \rightarrow qqH$ in LO



Survey of Feynman diagrams

Lowest order:



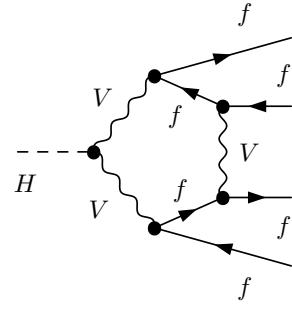
$$V = W, Z$$

electroweak $\mathcal{O}(\alpha)$ corrections:

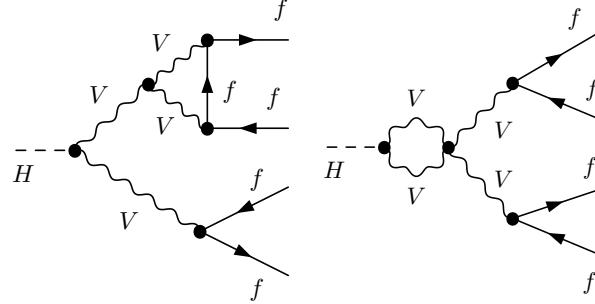
typical one-loop diagrams:

diagrams = $\mathcal{O}(200)$ per tree diagram

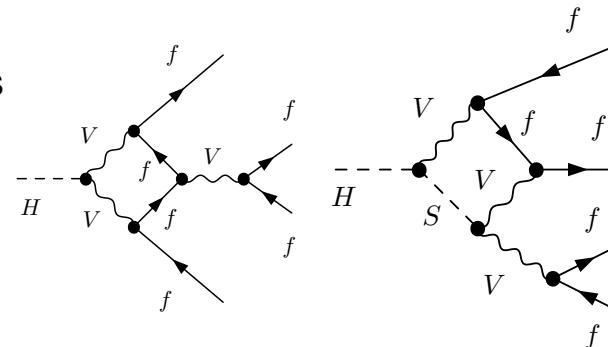
pentagons



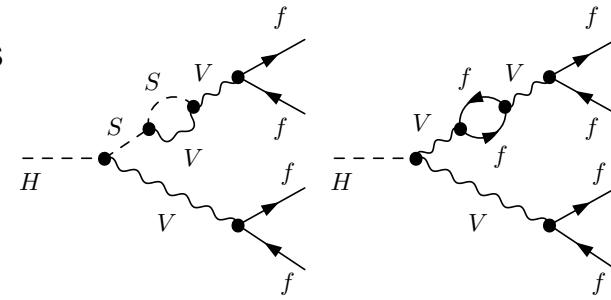
vertices



boxes



self-energies



Comments on the $\mathcal{O}(\alpha)$ calculation

Main complications in loop calculation:

- numerically stable evaluation of one-loop tensor integrals
 → improved reduction methods Denner, Dittmaier. '05
- gauge-invariant treatment of W and Z resonances
 → complex-mass scheme Denner, Dittmaier, Roth, Wieders '05

new concepts already used in
 $\mathcal{O}(\alpha)$ corrections to $e^+e^- \rightarrow 4f$ Denner, Dittmaier, Roth, Wieders '05
and $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha_s)$ corrections to $H \rightarrow 4f$
Bredenstein, Denner, Dittmaier, Weber '06/'07

Calculation of virtual corrections

Tools

- generation of Feynman diagrams with FeynArts version 1 and 3
- algebraic simplifications using two independent in-house programs implemented in *Mathematica*, one building upon FORMCALC
automatic translation into *Fortran* code
- reduction of tensor integrals according to
Denner Dittmaier, NPB734 (2006) 62 [hep-ph/0509141]
↪ numerically stable results
- scalar integrals: evaluated with standard techniques
and analytic continuation for complex masses

Algebraic reduction of tensor integrals

For details see NPB734 (2006) 62 [hep-ph/0509141]

- **2-point integrals:** numerically stable direct calculation
- **3-point and 4-point integrals:** Passarino–Veltman reduction
 - inverse Gram determinants of up to three momenta
 - serious numerical instabilities where $\det G \rightarrow 0$
(at phase-space boundary, but also within phase space !)

two hybrid methods

- (i) Passarino–Veltman \oplus expansions in small Gram and other kinematical determinants
- (ii) Passarino–Veltman \oplus seminumerical method \oplus analytical special cases
(numerical calculation of logarithmic Feynman-parameter integral and algebraic reduction to this basis integral)
- **5-point integrals** → five 4-point integrals Melrose '65; Denner, Dittmaier '02
stable reduction without inverse Gram determinants

Real corrections

Contributions

- real gluon radiation, processes with gq and $g\bar{q}$ initial states
- real photon radiation, photon-induced processes (γq and $\gamma\bar{q}$ initial states)

Matrix elements

- evaluated with [Weyl-van der Waerden spinor technique](#) Dittmaier '99
 → compact expressions
- checked numerically against MadGraph (for $\Gamma = 0$) Stelzer, Long '94

soft and collinear singularities:

regularized with small quark masses, absorbed via factorization in PDFs
two methods

- dipole subtraction formalism Dittmaier '99; Diener, Dittmaier, Hollik '05
- phase-space slicing numerical agreement within 0.3% ($1-2\sigma$)

Phase space integration

phase-space integration

- multi-channel Monte Carlo integration with adaptive optimization
Berends, Kleiss, Pittau '94; Kleiss, Pittau '94
⇒ arbitrary distributions possible (code to be checked)
- convolution with parton distributions within Monte Carlo
- two different generators with different implementations

Set-up of the calculation

- external fermion masses neglected whenever possible
(everywhere but in mass-singular logarithms)
- (complex) on-shell renormalization scheme
- G_μ scheme for electromagnetic couplings ($\alpha_{G_\mu} = \sqrt{2}G_\mu M_W^2 s_w^2 / \pi$)
accounts for electromagnetic running effects and universal corrections of the ρ parameter
- unit quark-mixing matrix (effect of realistic CKM $< 0.1\%$)
- MRST2004QED PDFs (include $\mathcal{O}(\alpha)$ QED corrections)
photon distribution function for proton
only four quark flavours for initial partons
- running α_s with 5 flavours and $\alpha_s(M_Z) = 0.1187$
- renormalization and factorization scale: default $\mu_F = \mu_R = M_H$
- no Higgs-boson decay included
- 10^7 weighted events without cuts, 2×10^7 events with cuts (~ 20 CPU h)

Checks on the calculation for $H \rightarrow 4f$

- UV structure of virtual corrections
 - independence of reference mass μ of dimensional regularization
- IR structure of virtual + soft-gluon/photon corrections
 - independence of $\ln m_\gamma$ (m_γ = infinitesimal photon mass)
- mass singularities of virtual + collinear gluon/photon corrections
 - independence of $\ln m_{f_i}$ (m_{f_i} = small masses of external fermions)
- gauge invariance of amplitudes with $\Gamma_W, \Gamma_Z \neq 0$
 - identical results in 't Hooft–Feynman and background-field gauge
Denner, Dittmaier, Weiglein '94
- real corrections
 - squared amplitudes compared with MADGRAPH Stelzer, Long '94
- combination of virtual and real corrections
 - identical results with two-cutoff slicing and dipole subtraction
Dittmaier '99
- two completely independent calculations of all ingredients !

Vector-boson fusion cuts

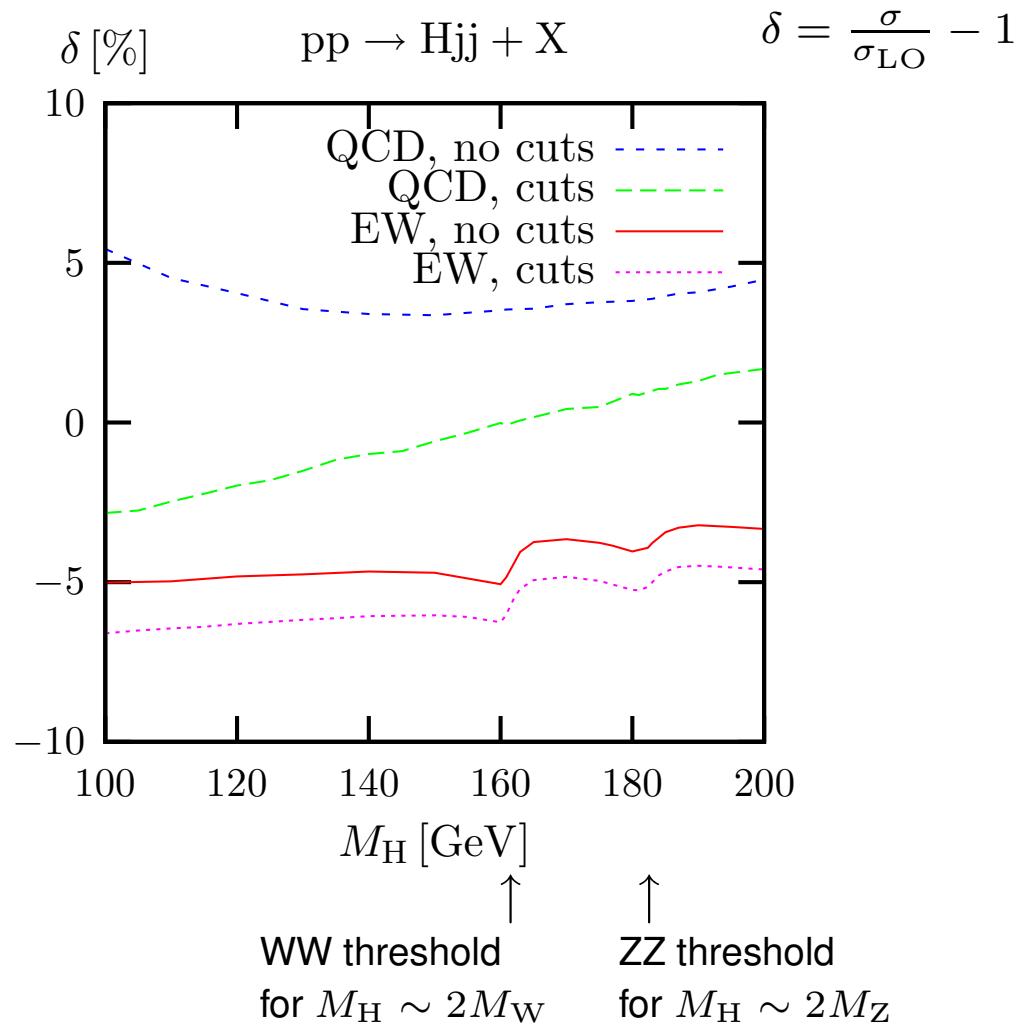
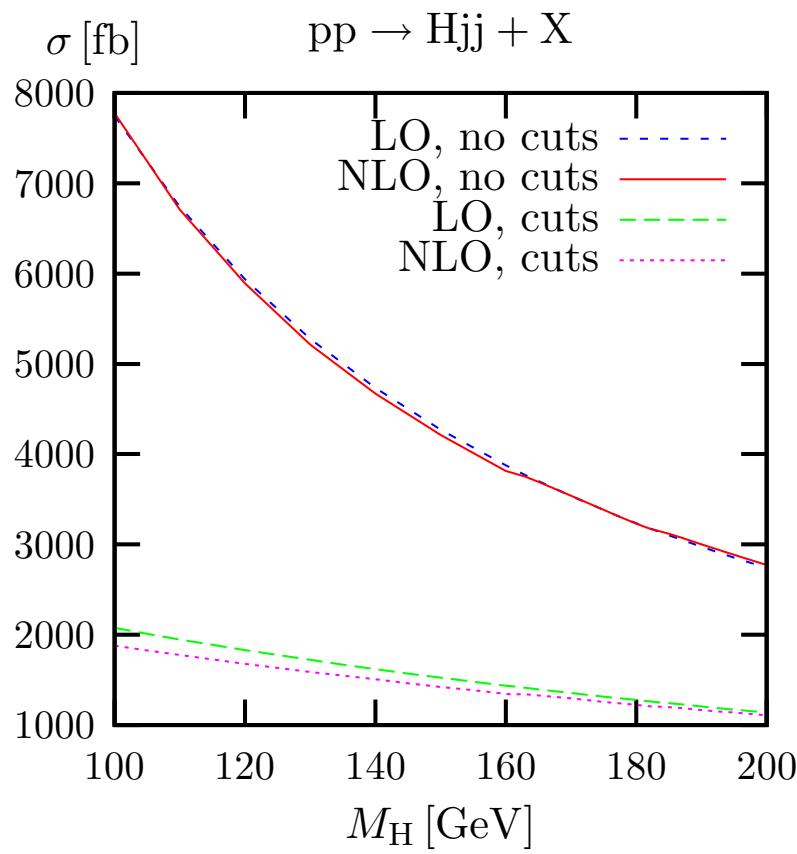
following Figy, Zeppenfeld '04

- jets defined via Tevatron run II k_T -algorithm Blazey et al '00
cluster jets from partons with $|\eta| < 5$
jet resolution parameter $D = 0.8$
real photons are recombined with jets
- require ≥ 2 hard jets with
 $p_{Tj} \geq 20 \text{ GeV}, \quad |y_j| \leq 4.5$
- define tagging jets
 $p_{Tj_1} > p_{Tj_2} (\geq p_{Tj_3})$
- require large rapidity separation of tagging jets
 $|y_{j_1} - y_{j_2}| > 4, \quad y_{j_1} \cdot y_{j_2} < 0$

Total cross section for $pp \rightarrow H + 2\text{jets} + X$

Ciccolini, Denner, Dittmaier

PRELIMINARY



electroweak (EW) corrections of similar size as QCD corrections
(partial) cancellation between EW and QCD corrections

Total cross section for $\text{pp} \rightarrow \text{H} + 2\text{jets} + X$

no cuts

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PRELIMINARY

M_{H} [GeV]	120	150	170	200
σ_{LO} [fb]	5936(1)	4271(1)	3536(1)	2743(1)
σ_{NLO} [fb]	5890(2)	4219(2)	3538(1)	2775(1)
δ_{EW} [%]	-4.81(2)	-4.70(2)	-3.65(1)	-3.33(1)
$\delta_{\text{EW,virt+real}}$ [%]	-5.68(1)	-5.74(2)	-4.79(1)	-4.60(1)
$\delta_{\gamma\text{-induced}}$ [%]	0.86(1)	1.04(1)	1.14(1)	1.27(1)
δ_{QCD} [%]	4.04(3)	3.47(2)	3.72(2)	4.48(2)
$\delta_{\text{QCD,diag}}$ [%]	4.22(3)	3.57(2)	3.75(2)	4.51(2)
$\delta_{\text{QCD,nondiag}}$ [%]	0.011(2)	0.028(2)	0.045(1)	0.047(1)
$\delta_{\text{g-split}}$ [%]	-0.015(1)	0.055(1)	0.104(1)	0.098(1)
$\delta_{\text{gg-fusion}}$ [%]	-0.176(1)	-0.171(1)	-0.171(1)	-0.175(1)

electroweak corrections $-3\% - -5\%$

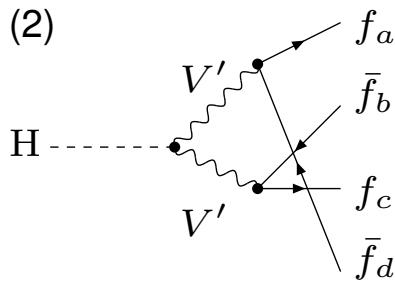
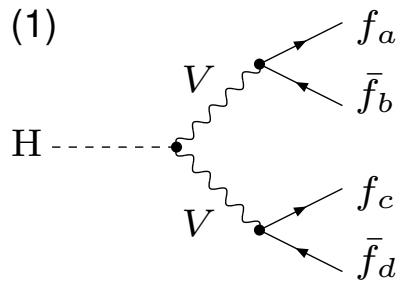
photon-induced corrections $\sim 1\%$

interference corrections $\sim 0.1\%$

5×10^7 weighted events
 ~ 120 CPU h on 3Ghz PC
per cross section

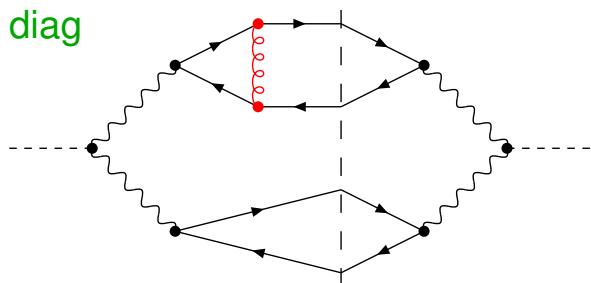
Classification of QCD corrections

Possible Born diagrams:

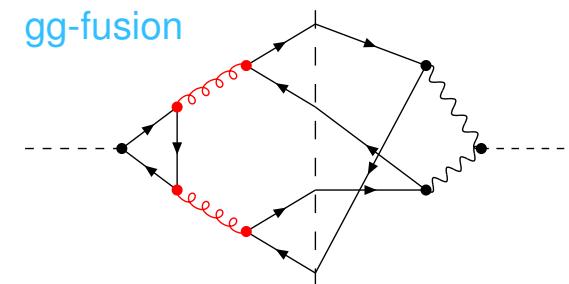
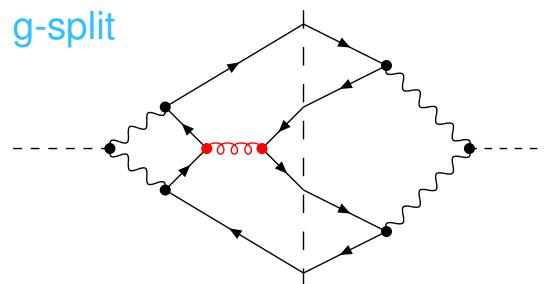
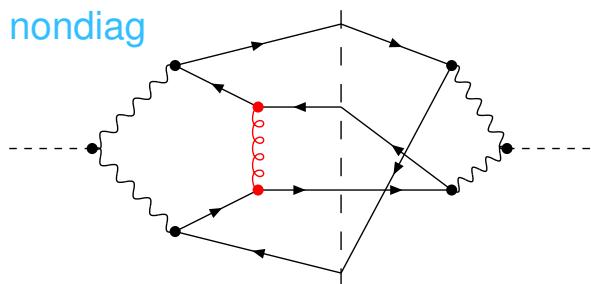


diagrams (2) only for
 $q\bar{q}q\bar{q}$ and $q\bar{q}q'\bar{q}'$ channels
(q' = weak-isospin partner of q)

Classification of QCD corrections into four categories: (typical diagrams shown)



diag = correction to W/Z decays



nondiag, g-split, gg-fusion = corrections to interferences (only for $q\bar{q}q\bar{q}$ and $q\bar{q}q'\bar{q}'$ channels)

Total cross section for $\text{pp} \rightarrow \text{H} + 2\text{jets} + X$

VBF cuts

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PRELIMINARY

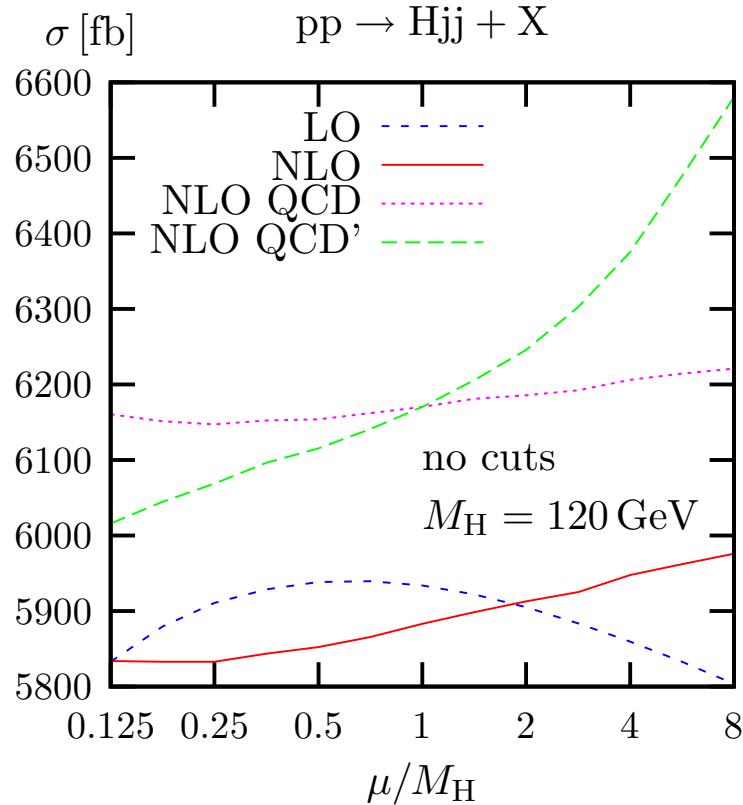
M_{H} [GeV]	120	150	170	200
σ_{LO} [fb]	1830.5(5)	1524.2(4)	1353.8(3)	1139.1(3)
σ_{NLO} [fb]	1678.7(9)	1422.9(7)	1293.4(6)	1106.0(5)
δ_{EW} [%]	-6.32(2)	-6.05(2)	-4.87(1)	-4.64(1)
$\delta_{\text{EW,virt+real}}$ [%]	-7.45(2)	-7.26(2)	-6.12(1)	-5.95(1)
$\delta_{\gamma\text{-induced}}$ [%]	1.137(2)	1.210(1)	1.255(1)	1.314(1)
δ_{QCD} [%]	-1.97(4)	-0.60(4)	0.41(4)	1.74(3)
$\delta_{\text{QCD,diag}}$ [%]	-1.96(4)	-0.56(3)	0.42(3)	1.76(3)
$\delta_{\text{QCD,nondiag}}$ [%]	-0.0110(2)	-0.0047(1)	0.0002(1)	0.0026(1)
$\delta_{\text{g-split}}$ [%]	-0.00829(7)	0.00736(9)	0.0212(2)	0.0236(2)
$\delta_{\text{gg-fusion}}$ [%]	-0.0272(2)	-0.0253(1)	-0.0238(1)	-0.0219(1)

electroweak corrections $-4\% - - 7\%$
 photon-induced corrections $\sim 1\%$
 interference corrections $\sim 0.02\%$

10^8 weighted events
 ~ 80 CPU h on 3Ghz PC
 per cross section

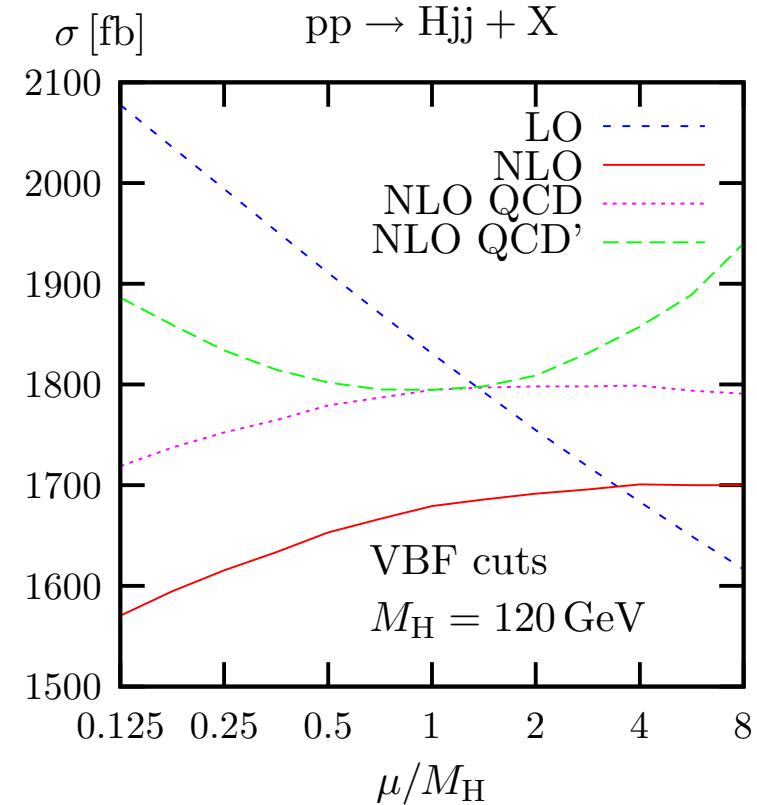
Scale dependence of total cross section for $pp \rightarrow H + 2\text{jets} + X$

$M_H = 120 \text{ GeV}$



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PRELIMINARY



$\mu_R = \mu_F \equiv \mu$ for LO, NLO and NLO QCD

$\mu_R = M_H^2/\mu$ for NLO QCD'

scale dep. at NLO: $\sim 10\text{--}20\%$ for $M_H/8 < \mu < 8M_H$

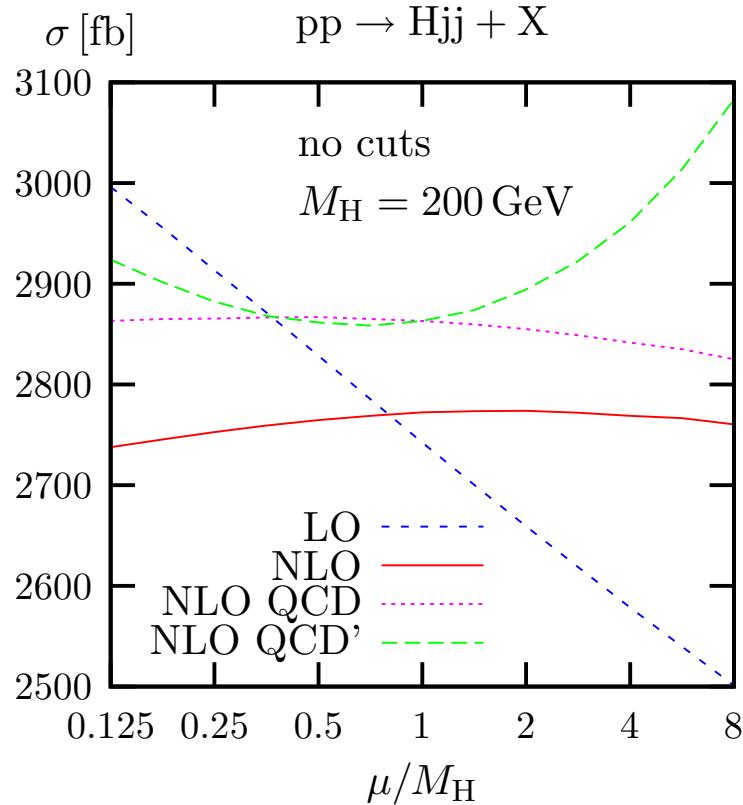
$\sim 3\%$ for $M_H/2 < \mu < 2M_H$

($\sim 30\%$ at LO)

($\sim 10\%$ at LO)

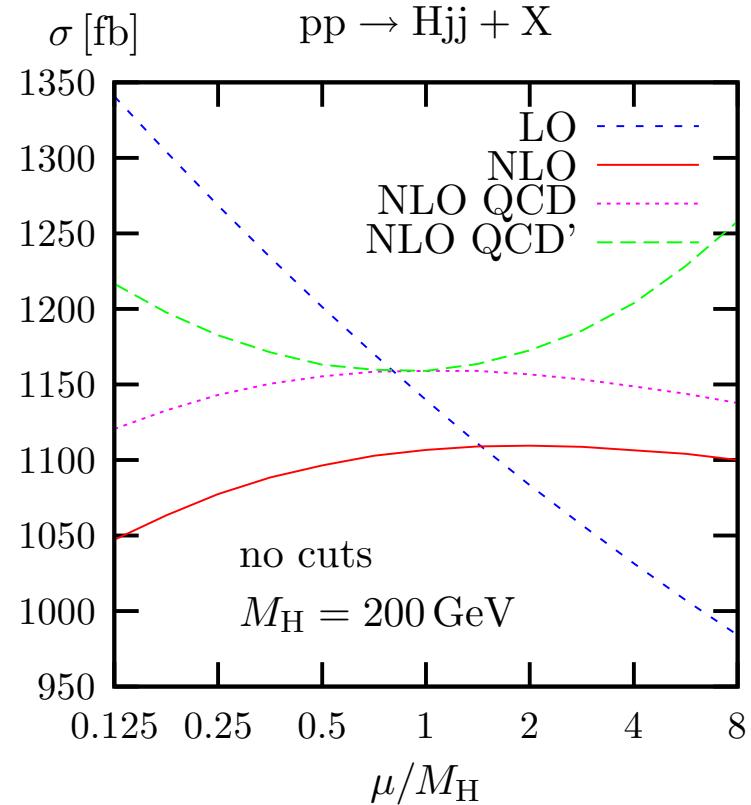
Scale dependence of total cross section for $pp \rightarrow H + 2\text{jets} + X$

$M_H = 200 \text{ GeV}$



Ciccolini, Denner, Dittmaier

PRELIMINARY



$\mu_R = \mu_F \equiv \mu$ for LO, NLO and NLO QCD

$\mu_R = M_H^2/\mu$ for NLO QCD'

scale dep. at NLO: $\sim 5\text{--}10\%$ for $M_H/8 < \mu < 8M_H$

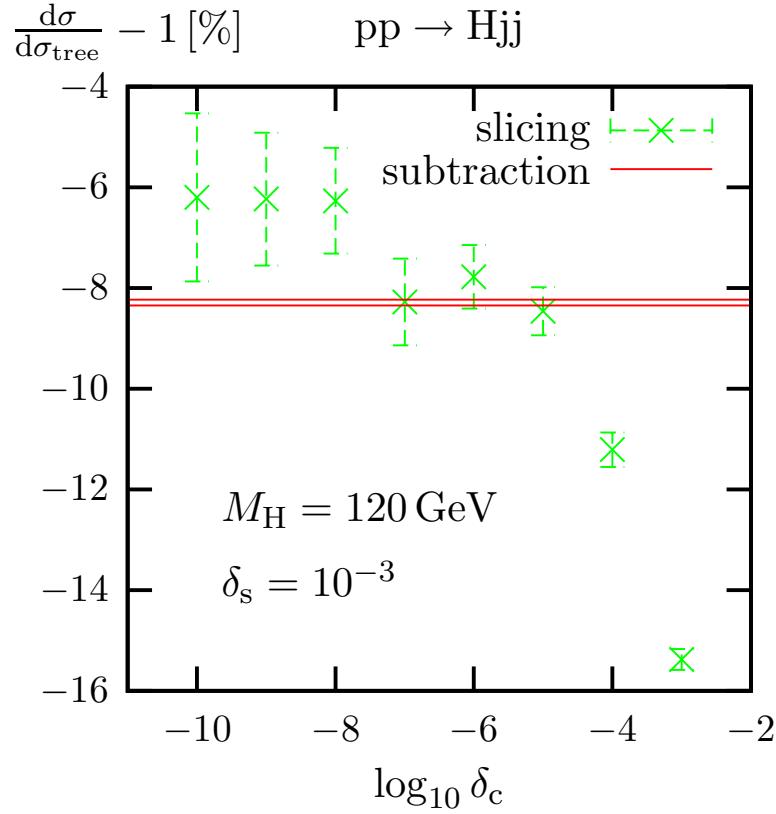
$\sim 2\text{--}3\%$ for $M_H/2 < \mu < 2M_H$

($\sim 20\text{--}30\%$ at LO)

($\sim 10\text{--}15\%$ at LO)

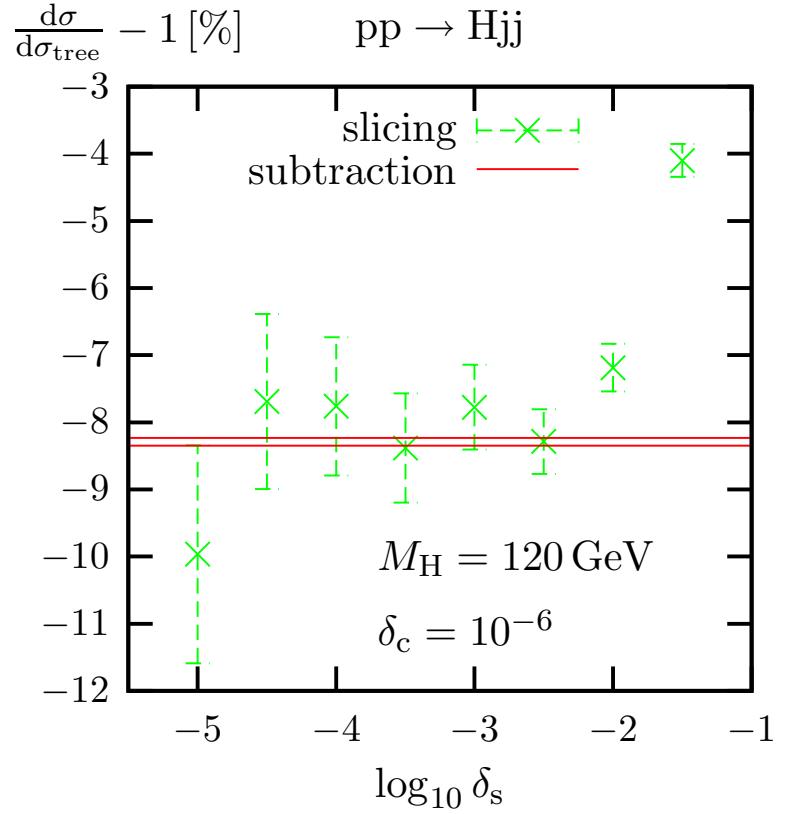
Comparison between slicing and subtraction methods

VBF cuts (10⁸ events)



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soft photon/gluon cut: $\delta_s = \Delta E_g / E_{\text{parton}}$

collinear photon/gluon cut: $\delta_c = 1 - \cos \theta_{\text{cut}}$

cuts are applied in CMS of incoming partons

Conclusions

Higgs production in vector-boson fusion $\text{pp} \rightarrow \text{H} + 2\text{jets} + X$ important for

- Higgs discovery at the LHC and Higgs-mass measurement
- measurement of HVV couplings

NEW: MC generator for $\text{pp} \rightarrow \text{H} + 2\text{jets} + X$ including

- full $\mathcal{O}(\alpha)$ electroweak corrections including photon-induced processes
 - ◊ W and Z resonances treated within the complex-mass scheme
 - ◊ tensor reduction numerically stabilized via seminumerical or expansion methods
- full $\mathcal{O}(\alpha_s)$ QCD corrections including s -channel diagrams and interferences

Preliminary results for the NLO corrections to $\text{pp} \rightarrow \text{H} + 2\text{jets} + X$

- electroweak corrections: $\mathcal{O}(5\%)$ and negative for $100 \text{ GeV} \lesssim M_{\text{H}} \lesssim 200 \text{ GeV}$
(partial) cancellation between EW and QCD corrections
- QCD interferences: $\mathcal{O}(0.1\%) \Rightarrow$ negligible